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ORIGINAL PAPER

Long-term vegetation development on a wildfire slope in Innerzwain (Styria, Austria)

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Abstract: Forest fires in mountainous areas can cause severe deforestation which can potentially trigger secondary natural hazards like debris falls and avalanches. We documented an extreme case study for the range of possible post-fire land cover (LC) dynamics. We investigated a 15-ha, steep (10°–65°) burnt slope in Styria (Austria) at elevation of 760–1130 m, which burned in 1946 and has not fully recovered to date. Seven 8-class legend LC maps were produced (1954, 1966, 1973, 1982, 1998, 2004, 2009) and integrated in a vector-based GIS, mainly by on-screen interpretation of aerial photos. Our aim was to clarify how post-wildfire LC dynamics take place on a severely damaged, steep slope and to give a basic projection of the future vegetation recovery process. The pre-fire *Pinus sylvestris* stands have been mainly replaced by *Picea abies* and *Larix decidua*. Regeneration proceeded mainly from the base of the slope upwards. All tree species together still cover no more than 40% of the slope after more than 60 years of recovery, while grassland communities and rock/debris areas have expanded. Multitemporal analysis showed a slow but steady increase in woodland cover. Degraded rock/debris areas, however, expanded as well because soil erosion and related debris flows remained active. Slope angle (with a threshold value of approx. 35–40°) seemed to control whether erosion or regeneration prevailed. According to a simple extrapolation, the slope will not reach its former condition before 2070. This extreme disturbance window of more than 120 years is owed to the steepness of the slope and to the shallow soils on dolomitic bedrock that were severely damaged by the fire. The neglect of any game fencing is a further factor slowing regeneration.

Keywords: wildfire, landcover change, temperate forest, aerial photos, soil degradation, vegetation development

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Introduction

Forest fires have destructive and constructive sides. On the negative side is the direct danger for humans and infrastructure and the economic loss to forest industries. On the other hand, in case of a moderate fire there may be positive effects in terms of species richness and biodiversity (Bell 1980; Moreno 1994; Keeley 2003; Moretti 2006; Wohlgemuth 2006). In the European Alps, wildfires are relatively rare compared to well-investigated boreal forests or Mediterranean regions (Catry 2009; Moreira 2009; Certini 2011; Amraou 2013). However, low-frequency high-severity fires are known to potentially have severe impacts on vegetation (Debano et al. 1998). Studies of fire frequency in the Alps and impacts on forest communities are mainly known from southern Switzerland (Condera et al. 1996; Tinner et al. 1999). For the Central Alps, historic fire frequencies of 200–600 yrs have been determined by Stähli et al. (2006) from charcoal in mires. In Austria, comparable investigations are rare apart from work in Tyrol reported by Sass et al. (2012) which points to similar fire frequencies. Styria is the Austrian federal state with the largest proportion of woodland, 61.4% of its total area (Austrian Forest Inventory 2012). Fire is generally very rare here and so are systematic investigations on land cover (LC) changes and vegetation recovery. According to our own investigations, anthropogenic fires are more common than natural ignitions, the main triggers being carelessness, railways and uncontrolled burning of residues, while lightning fires currently account for only 10%–15% of the fires (Vacik 2011).

In most of Austria, little research on wildfire has been carried out because its damage is negligible compared to that caused by windthrow or beetle infestations. However, new fire hotspots could potentially emerge in a changing climate. For example, the number of fires more than doubled in the dry summers of 2003 and 2007 (Gossow et al. 2009; Vacik et al. 2011). Furthermore, according to Tasser & Tappeiner (2008), the portion of woodland area in Austria will further increase due to climate warming and

changing land-use. Due to expanding forest areas caused by decreasing pasture and decreasing timber production, the number of fires is expected to further increase even without climatic forcing (Conedera et al. 1996). Forest areas could expand mainly on abandoned pastures at higher elevations where access is difficult for fire brigades. Moreover, the projected increase in the duration of summer droughts will increase the probability of lightning fires (Flannigan 1991; Balling 1992; Goldammer 1998; Piñol 1998). First evidence of this development has already been reported for Austria (Vacik et al. 2009).

In the steep mountainous areas of Austria, secondary natural hazards like rockfall, avalanches and debris flows are triggered by fire-driven deforestation which makes the speed of forest recovery particularly important for natural hazard assessment. Several large forest fires, mainly in Switzerland, have been investigated in terms of post fire succession, e.g. the Müstair fire in 1983 (Schönenberger & Wasem 1997; Wasem et al. 2010), the large fire at Leuk in 2003 in the Valais (Wohlgemuth et al. 2005) and the fire at Potokkessel in 1998 in Carinthia/Austria. The time taken for regeneration was usually in the range of years to decades. However, Sass et al. (2006, 2012) reported regeneration times ranging from several decades to even centuries for severely damaged forest fire slopes in the Tyrolean Limestone Alps. In the Eastern Alps, this long time taken for reforestation seems to be a peculiarity of steep slopes on limestone and dolomite bedrock. We found around 30 slopes (>15 hectares) on this type of substrate within the Northern Calcareous Alps that were deforested by fire, yet there were no such slopes on crystalline bedrock.

We investigated the "Innerzwain" site which is a very steep slope (>35°) developed on dolomitic bedrock. The slope burnt in 1946 and in 2013 was clearly distinguishable from surrounding forests by its more sparse vegetation. In terms of degree of damage and of recovery time, this case study is an extreme example of a severe ecosystem disturbance event. We monitored the very slow land cover development during the 60 years since the fire using aerial photographs to clarify how long-term vegetation regeneration has progressed on this severely damaged site. Our research objectives were (1) to describe the post-wildfire land cover dynamics on a steep alpine rural area over six decades, and (2) to infer how long will it take for the area to support land cover similar to the pre-wildfire situation.

Materials and methods

Study site

The study site is located in eastern Austria, about 6 kilometres south of the Hochschwab summit in the St. Ilgen valley (Fig. 1). This region is part of the Northern Limestone Alps in the Austrian federal state of Styria. It is a rural area with low population density and only minor infrastructure and industry. The climate of the southern Hochschwab region is humid and continental. The average July temperature at the nearby weather station Aflenz (6 km distance) is 15.5°C with maxima of around 32°C; the January mean is -3.2°C with minima as low as -25°C. Precipitation data of the nearby station at Buchberg (880 m, 2 km NW) and further surrounding stations was interpolated, resulting in estimated annual precipitation of 1300 mm at the elevation of the study site. Rain-bearing winds mainly come from the north (40%–55% of the total precipitation); however, there is also input of milder southern and south-eastern weather conditions. Arid conditions in summer are absent and even long periods without rain are very rare. The average vegetation growth period is 205 days.

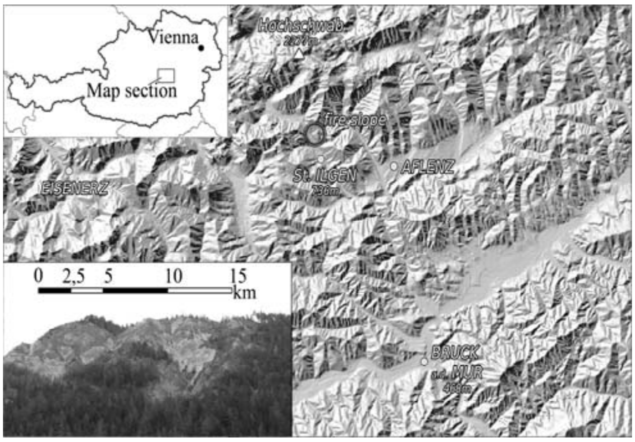

Fig. 1. Location of the study site "Innerzwain"

The bedrock of the region derives from the so-called Fölz facies of the upper Triad. The most important rock type on and around the slope is "Ramsaudolomit", a white to light grey coloured, entirely dolomitised limestone. It is a sharp edged, intensively fissured and brittle stone that produces vast amounts of debris. Usually, it forms steep jagged flanks or eroded landscapes. The typical soils on dolomitic rock are Rendzic Leptosols with A-C profiles and a topsoil layer of approximately 15 to 25 cm thickness. The climax vegetation on carbonate rock in the Hochschwab region is a mixed spruce – fir – beech forest (*Picea abies*, *Abies alba* and *Fagus sylvatica*). On poorer sites, including southerly exposed areas with thin soil cover, the pioneer trees larch (*Larix decidua*) and forest pine (*Pinus sylvestris*) dominate. In the understorey, richly flowered communities with *Erica carnea*, *Sesleria albicans* and *Calamagrostis varia* are found.

The investigated slope is located 500 m north of the small village Innerzwain (less than 20 residents today) and is oriented to the southwest. The total size of the forest fire area measured about 16 hectares. It extends from 100 m above the valley floor (760 m a.s.l.) up to 1,130 m, a.s.l. The average slope is 36° and reaches 65° in the upper parts. The affected area is bordered by a deep creek along the north-western edge and ends sharply at the north-eastern edge where the surface flattens. The nearest summits in the surrounding area are 1,000–1,500 m high.

The fire started on 03 Aug 1946 and lasted around 3 weeks. The summer of 1946 was exceptionally dry and had no rainfall for several weeks. During the same period, several large fires occurred in northern Tyrol as well (Sass et al. 2012). The cause of the Innerzwain fire is unknown but local people assume that it

was caused by berry collectors somewhere in the lower south-eastern part of the slope. In the first week only the southernmost creek was affected by the fire, but during the second week the fire went out of control and spread to an area twice as large around the northern creeks. All available fire brigades from the district Bruck were on duty. As the brigades did not have enough firehose, the work had to be done using simple fire beaters. The fire could not be extinguished by the fire-fighters; heavy wind restarted the fire several times and it was only stopped by rainfall after three weeks. It was a typical ground fire, burning very slowly without higher flames and it completely destroyed the top soil in most areas.

The vegetation destruction at the study site was clearly visible in 2013 from all over the valley (Fig. 1). According to foresters and to historical photos, the pre-fire vegetation of the site was a light forest of *Pinus sylvestris* mixed with *Picea abies* and *Larix decidua* including many natural glades covered with berry bush, and had never been used as timberland. On steep flanks, dwarf pine (*Pinus mugo*) occurred. This vegetation pattern is consistent with the forest found today around the burned area which consists of pine, spruce and larch, the frequency of *Pinus sylvestris* increasing with elevation. Reforestation measures started two years after the fire and were implemented by the school of forestry from Bruck and carried on until the late 1960s. Unfortunately, no documentation of the reforestation project is available. After the fire and until today, debris flow originating on the slope increased dramatically. Every few years, heavy rainfall events cause mudflows that damage croplands on the valley floor. In 2007, the land owners were forced to build an embankment to protect their farmlands.

Preparatory investigations

The land owner, contemporary witnesses, the local fire brigade and aged reforestation workers were interviewed to gather basic information on the timing and severity of the fire and the reforestation attempts. We also researched historical newspapers and local chronicles to confirm data and to find pre-fire photography. Unfortunately, some persons who were involved in fire fighting and reforestation have died in the meantime, and no accurate records were found for the reforestation attempts in the 1950s and 1960s.

The vegetation of the site was mapped two times in the field, first in August 2010 and again in May 2011. The mappings focused on tree species and age and these data were helpful later on for identifying tree species on historical aerial photos. Shrubs, gramineous and flowering plants were only identified occasionally to describe the plant community. Several soil pits were dug, supplemented by soil auger probing to measure soil thickness and profile.

Aerial photographs

A set of seven pairs of aerial photographs was obtained from the Austrian Federal Office for Surveying, dating from 1954–2009 (1954, 1966, 1973, 1982, 1998, 2004, 2009) and covering all decades in that time span. All aerial photos were taken between August and October. The spatial resolution of the scanned pictures ranged from 0.1 to 0.6 m per pixel. Before 1998, only greyscale pictures were available for the region, making it more difficult to identify tree species. The analogue photos all had different resolutions and most of them were not orthorectified. Thus, all photos had to be rectified on a point to point base to create matching orthographic pictures using the ArcGis 9 software. To accomplish this task, more than 150 reference points were set on each picture using prominent landmarks such as cliffs, boulders or roads.

The perimeter of the affected area was defined from the outline of the forest in 1954; the borderline at the upper elevation edge was determined after consultation with the land owner. The burned area measured 16 hectares which is less than half of what newspapers and fire brigades reported in 1946 (35 hectares). Since the aerial photographs differed widely in resolution, quality and colour, a relatively simple mapping key was defined to enable coherent analysis. Nine different land cover (LC) classes were defined:

- mature forest means adult trees of 2 or more meters height; close texture;
- immature forest means up to 2 m high, close texture;
- shrubs means single stands of bushes, might include grazed trees;
- grassland 100% means full coverage, uniform texture, without any debris;
- grassland 75% means grassland with sparsely dispersed debris/rocks;
- grassland 25% means sediments/rock with dispersed isolated grass patches;
- rock and debris means light-coloured, uniform texture;
- dead wood means area predominantly covered by fallen but not removed logs);
- stumps mean post fire cut down and removed trees, diameter probably 50 cm or more, only visible on 0.2 m resolution picture from 1954.

The classification was carried out manually by using the ArcGIS polygon tool. An automatic classification was not possible because most classes differed by structure rather than by color. Only the different shades of grass and rock were classified automatically from the raster images. Undersized areas smaller than one square meter were merged and/or deleted using the filter functions “boundary clean” and “majority”. Stumps were only classified in the first photograph from 1954. On later photographs it was not possible to identify them anymore because they had been removed or overgrown by grass. However, this class was helpful in clarifying the pre-fire vegetation pattern.

A deep creek in the centre of the area caused a prominent shadow which was different in size and shape in each picture. Thus, an overall shade area was defined covering all invisible regions; no classification was conducted in these parts because the changing shadow area in every picture would have flawed the results of the comparison. The complete area of all partial shades measures about two hectares.

The land cover transitions were finally analysed by intersecting the polygons of different age stages, rendering it possible to determine the size and type of land cover (LC) classes and their transformation into other classes over time (for example: area of grassland developing into shrub between 1954 and 1966).

Analysis of the digital elevation model

To investigate how the land cover (LC) transitions were distributed by elevation and slope, a digital elevation model (DEM) of 10 m resolution was obtained from the Styrian Federal Building Management Office. The DEM was divided into four elevation zones of identical surface area (Zone 1: 873–947 m, Zone 2: 948–995 m, Zone 3: 996–1,046 m, Zone 4: 1,047–1,157 m). Furthermore, the slope was divided into six areas of similar inclination; breaking values were calculated using natural breaks (16.5°, 24.5°, 29.5°, 33.5°, 37.5°, 41.8°, 47.2°) to retain a maximum variance between the classes. In the next step, LC transition polygons of each time interval were overlaid and cross-tabulated with elevation and slope maps.

Results

Current land cover and tree species

Today, new tree stands have developed mainly along the lower fringe and on a ridge approximately in the middle of the slope. In the other parts, few single trees have colonized. In the central area of the slope only *Picea abies* and *Larix decidua* were found. The influence of the surrounding *Pinus sylvestris* trees on the recovery of vegetation seemed to be negligible. *Larix decidua* reached about 6−10 m in height, *Picea abies* trees were restricted to 1−1.5 m due to intensive browsing by game. Tree ages were difficult to determine but most trees were probably around 25−30 years old. Only in the lower transition zone to the natural forest some examples of *Pinus sylvestris* were found that were at least 30−40 years old. A few individuals of *Pinus mugo* survived the fire in the northern area; however, they had not colonized the burnt area. Shrub vegetation was sparse in terms of both species and numbers. All shrubs were under considerable grazing pressure. Typically, *Erica carnea* in association with *Helleborus niger* and sporadic *Daphne mezerum* were found. The dominating grassland was a patchy cover of *Sesleria albicans* sometimes interspersed with moss and lichen. On some debris tongues large numbers of *Sempervivum* were found, accompanied by debris creepers such as *Linaria alpina*. On the steep and rocky upper slope typical species of calcareous grasslands had colonized (e.g. *Campanula cochleariifolia*, *Origanom vulgare*).

Land cover change over time

The aerial photograph of 1954 (Fig. 2) was taken eight years after the fire. It was the only photograph showing cut stumps (11% of total area). The main portion of the area was grassland or grassland with scattered debris. Both classes together covered 43% of the area. The remainder was rock/debris (19%), deadwood (8%), shrubs (5%), juvenile trees (11%) and some mature trees which might have survived the fire (3%). Rock and debris prevailed in steep regions while grassland dominated the flatter areas. There were no visible signs of reforestation in the entire area. Land owners reported that they had spread seeds and planted seedlings, but these were obviously too small to be detected on the aerial picture.

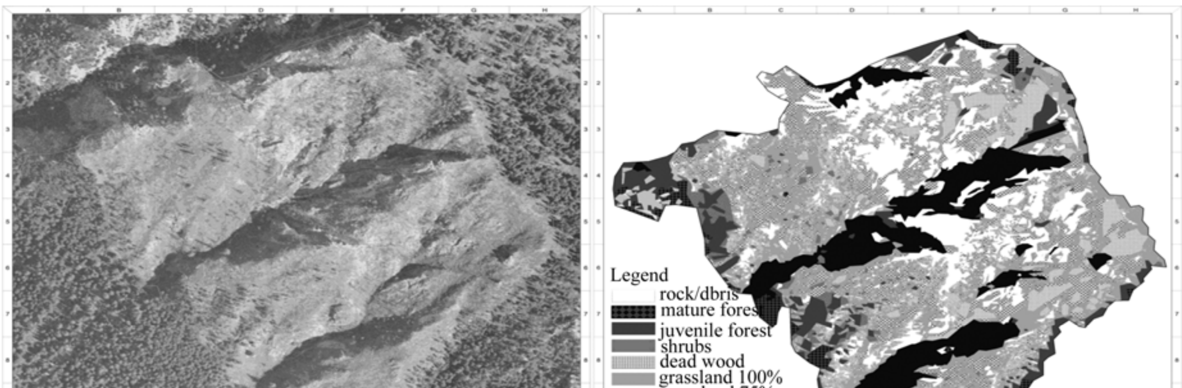

Fig. 2. Aerial picture of the Innerzwain slope in 1954 (left) and derived vegetation classification (right)

Classification maps similar to that shown in Fig. 2 (right) were produced for each aerial photo. Fig. 3 shows the situation in 1966 (the first photograph without stumps classified) compared to 2009. In 1966, 20 years after the fire, around one fourth of the burnt area was covered by woodland vegetation and 7% of the burnt area was occupied by full-grown trees. Dense grassland covered approximately 30% of the area and all tree stumps had disappeared or been replaced or overgrown by grassland. Modest recovery occurred originating from the upper elevation edge (mainly shrubs), but there was little or no development on the left and right flanks except for a small isolated belt of woody vegetation at the lower centre. In 2009, the wooded area was

mainly in the lower third and had increased considerably. The re-colonisation seemed to proceed mainly from the lower elevation edge upwards and consisted of larch, spruce and some fir (*Abies alba*). On some higher, relatively flat areas vegetation islands consisting mainly of larch had established.

Fig. 4 provides an overview of LC change between 1954 and 2009. The figure shows that the percentage of mature forest continuously increased over time from about 3% in 1954 to 30% in 2009. When the different time intervals between the aerial photos are considered, the growth rate has been remarkably constant. The proportion of young stands remained more or less constant over time. After an increase between 1954 and 1966, the shrub area was also relatively constant at around 12%. Surprisingly, rock/debris and rocky grasslands (<25% grass) also increased considerably in area, probably due to continued erosion. In 1973−1982 alone, two classes of grassland (100% and 75% cover) together lost around 7% of their area and were transformed into rock and debris areas. Clearly visible debris tongues developed on several steep areas formerly covered by grass. Thus, the growth of both forest and rocky areas was at the cost of the dense grassland areas which were gradually disappearing.

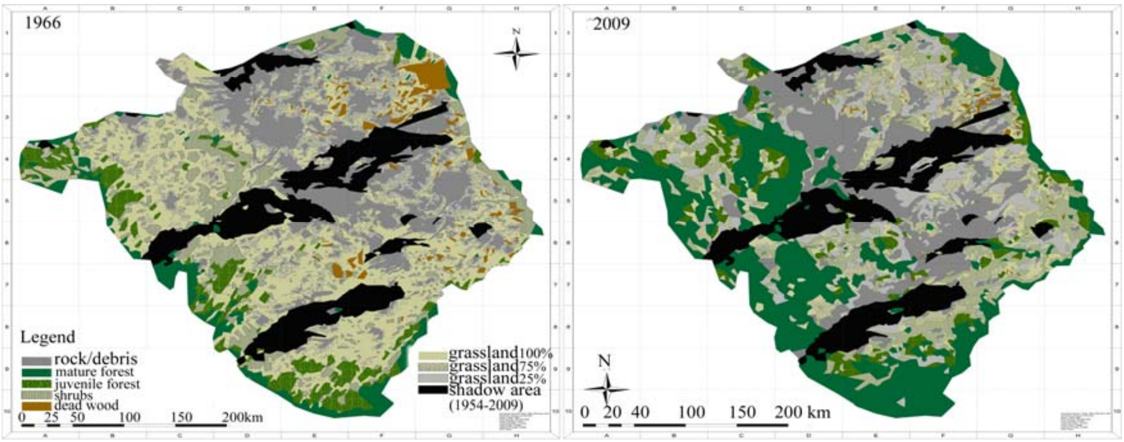

Fig. 3. Vegetation classification as derived from aerial pictures from 1966 (left) and 2009 (right)

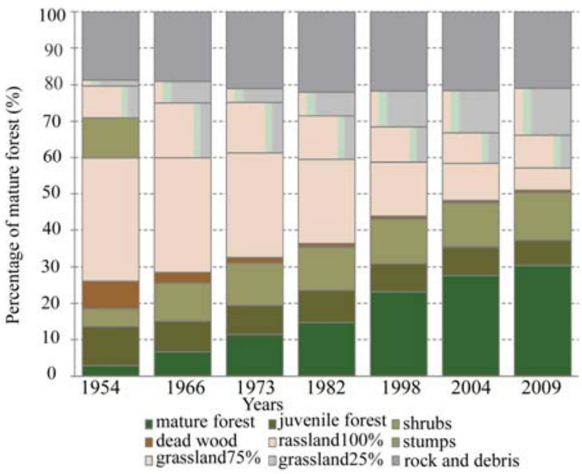

Fig. 4. Development of land cover (LC) classes between 1954 and 2009

A debris flow event occurred in summer 2007 which had visible impacts on the source area. Tons of debris were transported down from the debris areas and accumulated on croplands in the valley. The impact on the vegetation of the slope itself was minor. Only about 2% of the grassland was transformed into debris areas as most of the material was deposited outside of the investigated area. Fig. 5 further clarifies the transformation processes by showing which land cover (LC) class a preceding point in time developed into which LC class at the following point in time. To reduce the number of classes and improve readability, the following LC classes were merged: grassland 75% with grassland 100%; grassland 25% with rock/debris; and stumps with dead wood. It was evident that (1) mature forest, once established, always remained forest within the period of investigation; there was no noteworthy backward development. (2) The two classes of shrubs and immature forest were intermediate steps, they both transformed into forest while their total area changed little over time. They are, thus, an indicator of the rate of recovery. (3) Grasslands lost area for two reasons: First, they developed in part to shrubs, immature forest and later to mature forest; second, they were degraded to rock and debris areas. Some rock and debris developed to grassland; however, there was still a net reduction in the proportion of grassland. Topographic analysis revealed that the flatter grassland areas developed progressively to forest, while steeper areas were degraded.

Influence of elevation and slope

In the first 1−2 decades after fire, the woody vegetation recovered primarily in the lowest elevation zone (873−947 m), where 52% of the area was already wooded in 1966. At the other elevation levels, woodlands only reached coverage of 3%−11% by 1966. The zone of tree growth shifted progressively upslope during the following decades. Over the entire time period under investigation, the most extensive revegetation was observed at elevation level 2 (947−993 m). Between 1982 and 1998 alone, this area experienced an increase from 6.7% to 23.4% in mature

forest cover. At this time, the lower level 1 had already reached 71% vegetation cover and further development was much slower.

The rate of recovery was considerably modified by slope gradient (Fig. 6). Areas with gradients less than 30° showed considerably higher increases in cover of trees and shrubs. In 1954, the distribution of LC units on different gradient classes showed no identifiable pattern; woodland areas were quite evenly distributed across the range of slope gradients. By 2009, woodlands had preferentially colonized the less steep areas. Interestingly, in the last period (2004–2009) the greatest increase in cover of mature forest was observed on slopes of gradient >37°, which was because flatter regions were already occupied.

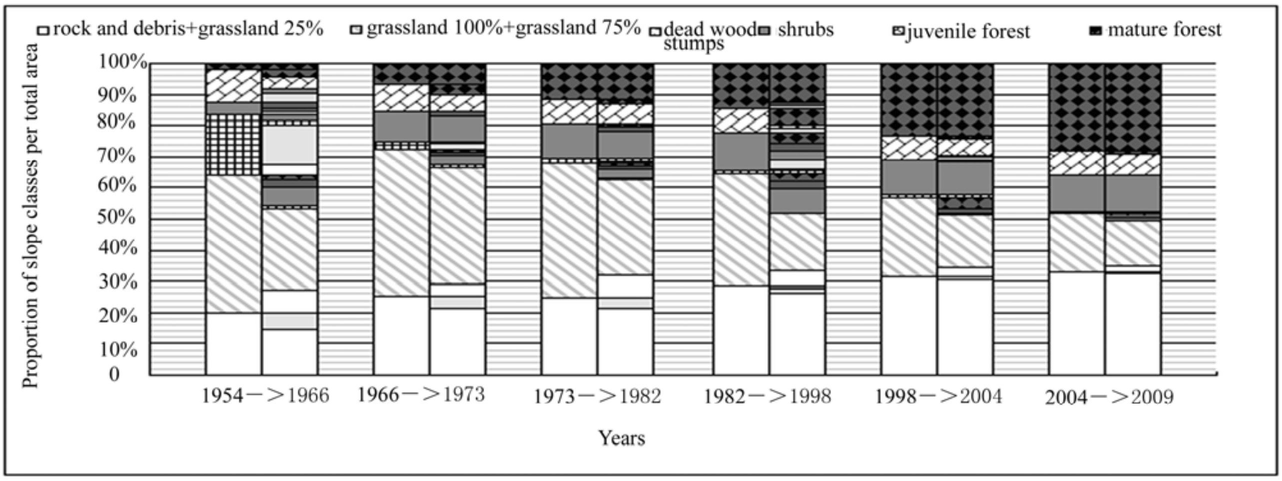

Fig. 5. Single step transformation and development of land cover (LC) classes between 1954 and 2009 (some classes combined for better readability: grassland 25% + rock/debris; grassland 75% + grassland 100%; dead wood + stumps; How to read the diagram (example first column): existing mature forest remained; existing young stands partly remained and partly developed to mature forest, shrubs and grassland; and so on.).

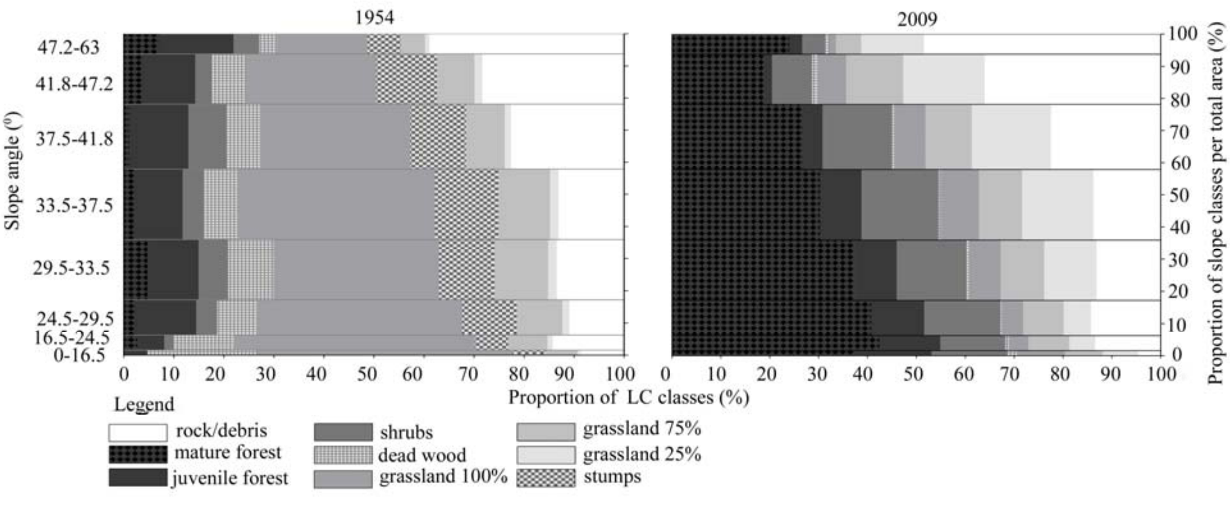

Fig. 6. Proportion of land cover (LC) classes per slope gradient interval in 1954–2009.

The development of rock and debris areas seemed to be particularly dependent on slope gradient. The total area of rock and debris had declined since 1954 by approximately 0.3% per year in the flatter areas (<33.5°), while it increased by approximately the same rate in the steeper areas (>33.5°). Most of these processes took place at the medium elevation level 3 (947 to 1046 m) where a mosaic of steeper and flatter areas was found. This differentiation process is also visible in Fig. 6, the land cover (LC) classes rock/debris and grassland 25% increased on all slope angle classes above 29.5°. (Fig. 6)

Discussion

Reasons for delayed regeneration

The recovery of vegetation after the massive forest fire on the Innerzwain slope in 1946 has progressed slowly. This has several explanations that can be divided into natural factors and human mismanagement. One of the natural factors causing severe soil

erosion and slow recovery is the dolomitic rock substrate, which readily decays and produces high amounts of debris and little residue for soil formation. The resulting thin soil cover was easily eroded by heavy rainfall. The spread of eroded areas might additionally be due to the fact that much of the duff layer was destroyed by the slow ground fire. In Portugal, soil degradation was eleven times greater when litter was removed manually after a fire (Shakesby et al. 1996).

The distribution of stumps in 1954 clearly indicates where reforestation would theoretically have been possible. The main management faults were delayed reforestation with inappropriate seedling species and failure to install game fencing. Sowing of seeds of *Picea abies* and *Pinus sylvestris* were probably the only reforestation attempts, while in such extreme locations, planting of potted plants would be advisable. Even this measure can only be successful if wildlife damage to seedlings is controlled. Rather than game fencing, we found a ruined hunting stand and two salt-lick sites on the slope (to attract deer). Consequently, the *Picea abies* stands showed evidence of extreme browsing damage and trees of 25−35 years in age reached only 1.5 m in height.

After the fire, some felled trees left on the slope provided a positive effect. Research at Müstair (Switzerland) showed that tree barriers and tree stumps stabilize the soil, enable shrub and grass growth and stop erosion (Schönenberger & Wasem 1997). At Innerzwain, although the soil was in fact stabilized on those areas, the re-growth of mature trees failed due to uncontrolled wildlife browsing. Many standing dead trees were left untouched for years and felled later. Felling those trees and laying them transverse to the slope angle would probably have been an appropriate measure to reduce soil erosion from other parts of the slope as well.

Tree species

While the pre-fire vegetation was a mixed forest mainly consisting of *Pinus sylvestris*, *Picea abies* and some scattered *Larix decidua*, the recovery in the first 25−35 years was dominated by *Larix decidua* alone. *Pinus sylvestris* played no role at all in reforestation. This difference between the pre- and post-fire vegetation in the montane belt was also reported by Schönenberger & Wasem (1997) in Müstair. *Larix decidua* prefers bare mineral soil as a seedbed (Schwitter 1999) and thus, burned areas offer favourable conditions for its germination (Schönenberger & Wasem 1997). *Larix decidua* also has a higher growth rate than other coniferous species during the first 30 years (Willuweit et al. 2003). On sites dominated by *Larix decidua*, soils often contain charcoal residues that indicate previous occurrence of forest fire. *Pinus sylvestris* might have high resistance to fire damage due to its thick bark. However, in terms of reforestation, this species is handicapped by its slow maturation. *Picea abies* has very low potential for regeneration after fire. It reaches sexual maturity at 30−50 years and does not sprout from burned stumps. Although in boreal forests, the thick layer of lichens often survives fire and serves as an ideal seedbed for *Picea abies*, if the topsoil is destroyed, regeneration from seed is difficult. It is also important to note that *Picea abies* takes about 10 years to reach 1 m height in the montane belt, while *Larix decidua* and *Pinus sylvestris* only take 4 to 5 years to reach the same height (Wasem 2009). The surviving stands of *Pinus mugo* did not show any substantial development over the first few decades. In the first 50−100 years after a forest fire the reproduction of *Pinus mugo* is generally limited (Sass et al. 2012).

Spatial and temporal patterns

Woodland vegetation was first to recover at the lower elevations and on flat topography. Once trees became established in a small isolated area, the regeneration process accelerated quickly around that plot or between two of those areas. The progression of colonization from the upper elevation and side borders was minimal even at low slope gradients. Post-fire development proceeded in two opposite directions: spread of forest on the one hand and of debris/bedrock areas on the other. Slope gradient and thus, intensity of soil erosion, seemed to be the main factor determining the balance between progressive revegetation and expansion of rock/debris area. On steep parts of the upper half of the slope, at least 2/3 of the pre-fire forest stands were transformed into degraded areas of rock and debris since 1946. Some of the fire-killed trees were still standing with their roots exposed. The soil has been washed away over the years; in some places, the uncovered root depth measured more than 30 cm. This situation is comparable to the Müstair wildfire of 1983 where significant soil loss from steep areas was evident (Schönenberger & Wasem 1997). The transformation process from grassland to rock/debris was also influenced by slope and micro-topography. Debris areas in convex terrain began to develop a thin layer of patchy grass after some decades while on concave terrain forms - especially at lower elevation - existing grassland was eroded or submerged by debris.

Long-term future development

On most fire-affected sites reported in the literature, regeneration proceeds rapidly in the first years after a fire and slows thereafter (Jahn 1970; Ahlgren 1974; Pausas 1999). At the Innerzwain slope, much longer time spans were required. The same is true in terms of erosion. The most intense soil erosion is usually recorded within the first two years after a fire (Shakesby et al. 1996; Minshall & Brock 1991; Meyer & Wells 1997) or longer if vegetation recovery is slow (Lathrop 1994). At the Innerzwain slope the situation was different: eroded areas continued to spread more than 60 years after the fire, but the rate of increase seemed to have slowed in the last decade (Fig.7). Thus, the slope was in a state of disturbed equilibrium. Woodland coverage increased almost linearly. If this rate of recovery is maintained in future, approximately 60% coverage will be reached by 2070 which would probably approximate the pre-fire condition. Young tree stands and shrubs act as a sort of "bio-reactor" with a constant coverage of around 20% transforming grasslands to wooded areas; once the mature tree stands reach their maximal area, the class of young tree stands will necessarily be reduced. Grass area increased rapidly after the fire, declined in later decades due to

natural succession, and was probably less than the pre-fire coverage by 2011. Given the tendency of the last decades, bedrock and debris areas are not expected to increase greatly and will concentrate on steep gradients, channels and depressions. These sites will probably show near zero recovery of higher vegetation for the next decades or longer.

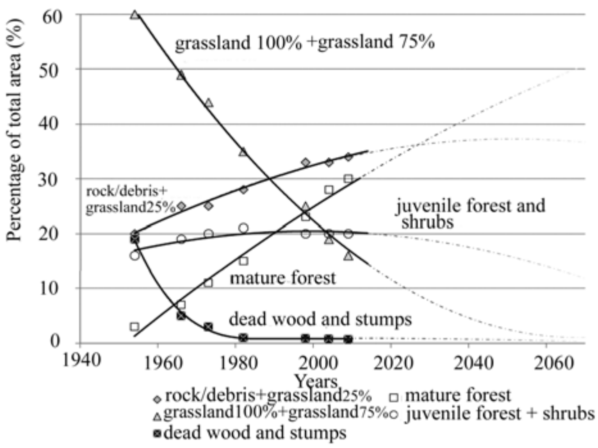

Fig. 7. Summarized development of the main land cover (LC) classes in the last decades, and assumed future prospects. Some classes combined for better readability.

We hypothesize that the remaining rock/debris areas will be very slowly revegetated by grass and trees in the future. However, the slope will differ from undisturbed slopes for many more decades due to the relatively high portion of debris and bedrock (and consequently, intensified geomorphic processes). On similar slopes in Tyrol it was found out that increased water runoff, rockfall and avalanche retard or even prevent vegetation recovery (Sass et al. 2006, 2012). This does not seem to be the case at Innerzwain with respect to tree cover. Given the observed pace of revegetation, the damage is not irreversible as one might suppose; the window of disturbance will extend, however, for at least one century.

Conclusions

At Innerzwain, 16 hectares of steep woodland were destroyed during a wildfire in 1946; only about 5 hectares (32%) recovered to mature forest over the subsequent 64 years. During the recovery process, the species composition changed and is now dominated by *Larix decidua* and *Picea abies* while some species of the pre-fire vegetation such as *Pinus sylvestris* are still absent. In the first 1–2 decades after the fire, land cover (LC) classes grassland 100% and grassland 75% reached their maximal area of coverage. Since then, mature forest, juvenile forest and rock/debris areas have expanded at the expense of the grassland LC classes. The rate of woodland recovery and the spread of rock and debris areas are mainly controlled by slope gradient. On gentler slopes, grassland was gradually replaced by immature and mature forest, while it was degraded to LC class rock and debris or grassland 25% on steeper areas (approx. >35–40°). Some of the eroded sites continued to increase in area more than 60 years after the fire.

The main reasons for the slow pace of revegetation are (a) the dolomitic bedrock produced large amounts of debris and little residue for soil formation; (b) infrequent heavy rainfall encouraged soil erosion; (c) anthopogenic reforestation was delayed and inappropriate species were planted; and (d) the absence of wildlife management resulted in extreme browsing damage. If the observed rate of recovery maintains over the coming decades, approximately 60% of the area will be revegetated to forest by 2070, which will approximate the pre-fire condition. Post-fire recovery was extremely protracted on steep slopes and calcareous bedrock, and this highlights fire prevention as an important management strategy to avoid or mitigate impacts of climate change.

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